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Burnett
Theories of Color-Perception

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THEORIES OF COLOR-PERCEPTION.

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BY

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FROM

THE AMERICAN JOURNAL OF THE MEDICAL SCIENCES.

JULY, 1884.

Phil 5645.1

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Through the vague and DIMLY Lighted
Realm of Philosophic Knowledge

Plunge Your Soul!

Be with Mortal Mind Keen sighted

Bring from Your College

By ...
1885
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THEORIES OF COLOUR-PERCEPTION.

By SWAN M. BURNETT, M.D.,

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It is a well-established principle of scientific philosophy, that, in the explanation of natural phenomena, that theory should stand nearest to acceptance which is most in keeping with laws that have been fully demonstrated, or that present some approach to harmony with authenticated facts of an analogous character. That a theory *can* account for phenomena is not a sufficient reason for its unequivocal acceptance; it must account for them in accordance with the laws that have been found to govern all phenomena of like nature.

When the action of such laws is obscure and not clearly understood, and when there are no closely allied facts to fall back on in the construction of a theory, then we are permitted to indulge in speculations, which can be provisionally accepted until other theories, better substantiated by newly discovered facts, arise to take their places; and as the laws controlling any manifestation of nature are not yet, and from the necessity of the case probably never will be, fully understood, no theory concerning any phenomenon can be considered as fixed. The truly scientific mind, therefore, always holds itself in readiness to change its attitude towards any of the workings of nature as our constantly increasing knowledge may demand.

The question of colour-perception is one which opens a very wide field for the display of speculation, and yet the theories on the subject have been, considering this fact, wonderfully few. As we only came on to anything like accurate knowledge concerning the properties of light with Newton, we are justified in regarding the truly scientific ideas concerning the perception of colour as beginning with him.

Theories of Newton and Young.—Since Newton looked upon light as the result of the action on the eye of corpuscles of a material kind emanating from luminous bodies, it was natural for him to suppose that the size of these corpuscles or the velocity with which they travelled, had something to do with the perception of colour, since it was on these qualities of the emitted particles that he accounted for the physical constitution of light.

and for its decomposition into the solar spectrum. We accordingly find him adopting the theory that the particles of light excite the retina according to their nature and bigness, and thus give rise to different sensations of colour. His views on the subject may be inferred from the following extract from the fourth edition of his *Opticks* (1730) pp. 318-319. They are in the form of questions which he appended to Book III. of the third edition, the last which had revision at his hands.

"Qu. 12. Do not the rays of light in falling upon the bottom of the eye excite vibrations in the *Tunica Retina*? Which vibrations being propagated along the solid fibres of the optic nerves into the brain, cause the sense of seeing. For because dense bodies conserve their heat¹ for a long time and the densest bodies conserve their heat the longest, the vibrations of their parts are of a lasting nature, and, therefore, may be propagated along solid fibres of uniform dense matter to a great distance, for conveying into the brain the impressions made upon all the organs of sense. For that motion which can continue long in one and the same part of a body, can be propagated a long way from one part to another, supposing the body homogeneous, so that the motion may not be reflected, refracted, interrupted, or disordered by any unevenness of the body.

"Qu. 13. Do not several sorts of rays make vibrations of several bignesses, which, according to their bignesses, excite sensations of several colours, much after the manner that the vibration of air, according to their several bignesses excite sensations of several sounds? And particularly do not the most refrangible rays excite the shortest vibrations making a sensation of deep violet, the least refrangible the longest for making a sensation of deep red, and the several intermediate sorts of rays, vibrations of several intermediate bignesses to make sensations of the several intermediate colours?

"Qu. 14. May not the harmony and discord of colours arise from the proportions of the vibrations propagated through the fibres of the optic nerves into the brain, as the harmony and discord of sounds arise from the proportions of the vibrations of the air? For some colours if they be viewed together, are agreeable to one another, as those of gold and indigo, and others disagree."

Essentially the same ideas were expressed by the eminent physiologist and physician, Wm. Potterfield, in his *Treatise on the Eye, the Manner and Phenomena of Vision*, in two volumes, Edinburgh, 1759. We find in vol. 2, pp. 342-343, the following paragraph:—

"§ 5. The third manner in which colours may be considered is the passion of our organ of sight, that is, the motions or vibrations excited in the fibres of the retina by the impulse or stroke received from the rays of light; which motions or vibrations being propagated along the solid fibres of the optic nerves into the brain, cause the sensation of colours. For the rays of light being corpuscles of different magnitudes, will, by striking the retina, excite vibrations of different bignesses, which, according to their bignesses must excite sensations of several colours, much after the manner of the vibrations of air, according to their several bignesses excite sensations of several sounds; and particularly the shortest or most refrangible rays will excite the shortest and weakest vibrations for making a sensation of deep violet, the largest or least refrangible, the largest and strongest vibrations for making the sensation of deep red, and the several intermediate sorts of rays, vibrations of several intermediate bignesses to make sensations of the several intermediate prismatic colours; but when the several heterogeneous rays are blended together promiscuously, they must then, in falling upon the *retina*, excite several other different sorts of vibrations for making the sensations of the several compound colours, which will, therefore, differ among themselves according as the light is composed of more or fewer of the different coloured rays or as they are mixed in various proportions."

¹ It will be observed that Newton in the discussion of this question recognizes the analogy or identity of light and heat.

Accepting the theory of light as promulgated by Newton, nothing could be simpler or more satisfactory than this hypothesis, and it is wrought out in that direct manner characteristic of the great philosopher. No other important explanation of the phenomena of colour-perception, so far as my knowledge extends, was advanced until the overthrow of Newton's emission theory of light and the adoption of the undulatory hypothesis. As is well known, the man who was mainly instrumental in this revolution of opinion was Thomas Young, another of England's great scientific geniuses. He was not content with substituting the undulatory for the emission theory, but deemed it necessary to do away with Newton's simple explanation of coloured vision and put forth one which, in its attempt at simplicity, becomes involved in a series of complexities and inconsistencies which is rarely met with in the history of science. Young believed it impossible for as many vibrations as answered to the chief colours of the spectrum to take place at one and the same point of the retina at one and the same time. This, so far as I am able to learn, was the sole cause for his refusal to accept Newton's theory and for the adoption of the one which is now known by his name and has had an accepted place in the scientific world for eighty years.

Since all the vibrations could not be reproduced at the same point of the retina at the same time, he considered it necessary to reduce the spectrum to a few fundamental colours and make the others but a combination of these. He accordingly fixed upon three colours, which he called primary, and supposed that there existed in the retina three fibres which responded to the vibrations representing them. The three colours he chose as primary were red, green, and violet. White light was the sensation produced by an affection in a certain degree of all three fibres, and the secondary colours came from a combination in varying proportions of two or more of the fundamentals. The ingeniousness of the theory was very captivating, and in one way or another nearly all of the phenomena of coloured vision could be accounted for by it; so that, until within a very few years, it held sway over the scientific mind of the whole world, particularly after it had received the sanction of so eminent an authority as Helmholtz.

Objections to Young's Hypothesis on Physical Grounds.—In the first place, the retina, in addition to its function as a receiving and transmitting organ, is made by this theory into a differentiating apparatus as well. This is rendered necessary because of Young's disbelief in the capacity of the retina to act as a receptacle for vibrations after the manner of simple bodies. There is something remarkable in a kind of hitch we sometimes find in the intellectual workings of even our greatest men. It has always been a wonder to scientists that Newton, with a mental power capable of originating so far-reaching a theory as the law of gravitation,

should pass by the undulatory theory of Huygens as not capable of explaining phenomena of light.¹

And it is equally astonishing that Young and all those who have accepted his theory should have overlooked one fact which must have been apparent upon a moment's reflection.

Since the emission theory had to go to the wall, it became necessary to search for some origin of the vibrations of the ether, and this was most naturally found in the substance of the luminous body itself. Researches in the domain of molecular physics seem to leave no doubt that when bodies are heated up to the point of luminosity (or when heated at all, for that matter), the ultimate molecules of which they are composed are put into a state of vibration, and it is this vibration which, communicated to the ether, is the first link in the chain of phenomena which finally ends in the sensation of light. It must be accepted as a fact, therefore, that all the vibrations found in the ether must have had their existence primarily in the molecules of the luminous body. When a body is brought to a white heat, for example, the molecules of which it is composed must make all those phases of vibrations which correspond to every colour into which white light may be decomposed, and must make them at one and the same time. In no other way is it possible to explain satisfactorily and consistently the various vibrations of the ether and the manner in which they are brought about.

Now, Young must have known this, for he could hardly have supposed that there were three separate and distinct fibres in all luminous bodies giving out white light, particularly in those bodies which so far as it is possible to ascertain are strictly homogeneous and simple. If this is true of the originating body, why should it not be true of the body receiving and transmitting the vibrations? Why is it necessary to assume the existence of three separate fibres in the retina whose office it is to receive the vibrations,

¹ The position of Newton in regard to an ether was a peculiar one, and deserves notice here, since it has a bearing on the subject in hand. He by no means denied its existence, but on the contrary believed in it strongly, and even went further in the applications of its use than is contended for now. Thus he says in his *Opticks*, p. 328 :—

"*Qu. 23.* Is not vision performed chiefly by the vibrations of this medium excited in the bottom of the eye by the rays of light and propagated through the solid, pellucid, and uniform capillamenta of the optick nerves into the place of sensation? And is not hearing performed by the vibrations either of this or some other medium excited in the auditory nerves by the tremors of air and propagated through the pellucid and uniform capillamenta of those nerves into the place of sensation? And so of the other senses.

"*Qu. 24.* Is not animal motion performed by the vibrations of this medium, excited in the brain by the power of the will, and propagated from thence through the solid, pellucid, and uniform capillamenta of the nerves into the muscles for contracting and dilating them? I suppose that the capillamenta of the nerves are each of them solid and uniform, that the vibrating motion of the ethereal medium may be propagated along them from one end to the other uniformly and without interruption; for obstruction in the nerves causes palsies."

It will be seen from this extract that he considered the ethereal medium to pervade solid bodies and to take part in the phenomena of light, but it was a secondary part.

when the body giving rise to these vibrations is simple, and with its molecules so arranged that they can vibrate at one and the same time in the different phases corresponding to the different wave-lengths representing the various colours? This, it seems to me, is a death-blow to the sole objection advanced against the adaptation of Newton's views to the undulatory theory.

Neither is there any support for Young's theory from analogy. Certainly it is not to be found in the sense of hearing which has always been considered as most closely allied to that of vision. On the contrary, it seems the rather to offer evidence against it. Take the *membrana tympani*, for example. It is a simple membrane, and as far as regards any action of sound-waves homogeneous in structure, and yet it can take up and carry to the chain of small bones, correctly and without any alteration in character, an infinite number of different aerial vibrations at the same time. In an orchestra composed of 100 pieces the trained ear of the leader can often detect a single false note, and yet this is only one of many hundreds of thousands of tones and over-tones which are simultaneously taken up by this small membrane and faithfully transmitted to the ossicles and thence to the auditory nerve. And even when we reach the labyrinth which bears a still closer analogy to the retina in function we find there nothing which would substantiate Young's theory. Even if the organ of Corti were the finally differentiating organ, which no one will, I presume, assert, there is a cord for every tone, and three are not called upon to do the service of hundreds or thousands.

And again, if a fibre is so constructed as to be in harmony with waves of a certain length, it becomes thereby physically incapacitated from responding to waves of other lengths. This is one of the fundamental laws of wave-motion, and its greatest beauty is shown when it comes to be applied in the domain of molecular physics. This law finds no exact application in the theory of Young. He assumes three retinal fibres, red, green, and violet, which are attuned in harmony with the red, green, and violet waves. Now in accordance with this law these fibres should respond only when acted on by wave-lengths corresponding to the colours they represent. If the red fibre is accurately attuned to red rays, it should not be affected by the green or violet, nor the green by the red and violet. Still for a satisfactory explanation of some of the phenomena of coloured vision Young was obliged to suppose that all the fibres were affected by the rays of each of the other two colours, though in varying degrees; and not only that, but they must respond to wave lengths not peculiar to any one of the three. Thus yellow, which is not considered a primary colour, but a combination of red and green, has a distinct wave-length of its own, being about $\frac{1}{42,016}$ of an inch (5,808/10,000,000 mm.).

The "rays of light" were solid bodies which coming in contact with the ether contained in the retina set it in vibration; which vibration was conveyed along the "solid and pellucid" optic nerve to the brain.

There is no fibre corresponding to this, but for the perception of yellow there must be an affection of the red fibre $\frac{1}{27,640}$ of an inch (7,000/10,000,000 mm.) wave-length, and the green fibre $\frac{1}{40,230}$ of an inch wave-length (5,271/10,000,000 mm.). So that for the perception of yellow it is necessary for its corresponding wave to affect, not a fibre attuned to its own length, but two others which are adapted to phases of vibration different from its own and different from each other, a state of affairs which the molecular physicist must look upon as absurd. We have, moreover, direct proof that yellow is not a compound colour, for in Hippel's case of unilateral colour-blindness (Gräfe's *Archiv*, xxvi. 3) the yellow as seen by the affected eye had no difference as regards intensity or tone from that seen by the unaffected eye; showing that yellow cannot be composed of red and green, or at least that it can be produced independently. If it were a compound colour, in green-blindness it would appear according to the three-fibre theory as red, in red-blindness as green.

Besides, in giving this amount of forced latitude to his theory, Young destroyed the cause for its existence, since he plainly failed to get rid of the very thing he wished to avoid, namely, the action of a number of wave-lengths on the retina at the same place and at the same time.

The Theory of Prof. Hering.—The theory first advanced by Prof. Hering of Prague¹ differs in many important details from that of Young, though they have this in common, that they require the presence of three peculiar anatomical elements in the retina. In Young's, as we have seen, they are fibres. In Hering's they are chemical substances, which he designates as the *white-black*, the *red-green*, and the *blue-yellow*. Hering supposes that these substances are acted upon by light in a peculiar manner. The red-green substance is affected by no colours but red and green, and these act upon it in opposite ways. Red light, for example, acts in a decomposing or dissimilating (*D*) manner on this substance and produces the sensation of red; green light acts in a regenerating or assimilating (*A*) manner on it causing the sensation of green. Blue has an *A*-action on the blue-yellow substance; yellow a *D*-action. It will be seen that he recognizes four fundamental colours instead of three, which are divided into two pair, the components of each pair being antagonistic; for when the *A*- and *D*-action on any substance are equal the effect is neutral, and no sensation is the result. On the third substance, the black-white, white light acts in a dissimilating manner, while black causes an assimilating action. Moreover, both the other substances are affected in an *A*- and *D*-manner by means of white and black.

The peculiarities of this theory are, that it makes the perception of black a positive action instead of a simple absence of sensation, the so-called complementary colours, antagonistic, and the white resulting from

¹ Lehre von Lichtsinne, Vienna, 1878.

their combination the result of subtraction rather than of addition, as has been heretofore believed.

Objections to Hering's Theory on Physical and Physiological Grounds.—This theory has no more basis in fact or analogy than that of Young. The three chemical substances have never been chemically or otherwise demonstrated, nor is this peculiar action of light found represented in any degree in any other function of the animal economy or in the inorganic world. It is not more simple than Young's, and it is open to the same charge of inconsistency. The substances which are supposed to be peculiar to a certain pair of colours are not so, but are likewise acted on by the light peculiar to one of the others. The red-green substance and the blue-yellow substance are both affected, in addition to their own colours, by white and black. Why, it may be very pertinently asked, if we are going to imagine a number of chemical substances, should we limit ourselves to three? We have just as much ground for supposing a half-dozen or more as three. Or, if we are not to have these substances fixed at three, and one substance can respond to the light peculiar to another, why make any division at all? Why not simply take one substance and make it responsive to all the wave-lengths represented by the principal colours of the spectrum? Besides, red and green, and blue and yellow, are not complementary colours—that is, a mixture of the two does not produce white light. Red must be combined with bluish-green, and yellow with ultramarine blue, before we can have white light; and, moreover, the white which is the result of these combinations is not less in intensity than either of the two colours which have produced it, as must be the case if it be the result of subtraction instead of addition, as is contended for by Hering.

Objections to the Theories of Young and Hering from the stand-point of Abnormal Colour-perception.—At the time Helmholtz gave his adherence to the theory of Young, the subject of colour-blindness had not been studied in such detail as it has been within the last eight or ten years; and as by various turnings and twistings it could be made to account for nearly all the phenomena of colour-perception and for many of those of colour-blindness as then understood, the great scientist lent it the weight of his name and authority, and thus made its general acceptance almost inevitable. When, however, Holmgren introduced his method of examining the colour-sense, which made the detection of defects in colour-perception easy, an impetus was given to a more minute study of these abnormalities, and certain facts were brought to light which had to be harmonized with the accepted theory of colour-perception; for it is evident that any acceptable theory of colours must account in a consistent and satisfactory manner not only for all the phenomena of colour-perception, but also for those of colour-blindness.

According to the generally accepted belief among the supporters of the Young-Helmholtz theory, colour-blindness can be of only three kinds (ex-

clusive of total colour-blindness), according as one or the other of the three fibres is missing or hindered in the proper performance of its function ; that is to say, we have red-, green-, or violet-blindness.

Accepting the theory, no other division of abnormal colour-perception is possible ; and, moreover, certain facts seemed to lend it support. Now, if the theory were simple and each fibre responded alone to one set of vibrations, the manifestations of abnormal colour-perception would be simple, unmistakable, and consistent ; but because the theory is not simple, the phenomena of colour-blindness, according to this theory, become exceedingly involved, and are unravelled with the greatest difficulty. Helmholtz has worked out theoretically the manifestation of abnormal colour-perception for red-blindness as compared with the sensation of the normal eye, as follows : " Spectral red, which feebly excites the perceptive organs of green, and scarcely at all those of violet, must consequently appear to the red-blind a *saturated green of a feeble intensity*, more saturated than normal green, into which a sensible portion of the other primitive colours enters. Feebly luminous red, which affects the perceptive organs of red in the normal eye sufficiently, does not on the other hand sufficiently excite the perceptive organs of green in the red-blind, and it therefore seems to them black. Spectral *yellow* seems to them a *green saturated and intensely luminous*, and as it constitutes the precisely saturated and very intense shade of that colour, it can be understood how the red-blind select the name of that colour, and call all those tints that are, properly speaking, green, *yellow*. *Green* shows, as compared with the preceding colours, a more sensible addition of the other primitive colours ; it then appears, consequently, like a more intense but whitish shade of the same colour as yellow and red. The greatest intensity of light in the spectrum, according to Seebeck's observations, does not appear to the red-blind to be in the yellow region, as it does in the normal eye, but rather in the blue-green. In reality, if the excitation of the perceptive organs of green, as it was necessary to assume, is strongest for green, the maximum of the total excitation of the red-blind must be found slightly toward the blue side, because the excitation of the organ perceiving violet is then increased. The white of the red-blind is naturally a combination of their two primitive colours in a determinate proportion, a combination which appears blue-gray to the normal sight ; this is why he regards as gray the spectral transition colours from green to blue. Then the other colour of the spectrum, which they call *blue*, preponderates ; because indigo-blue, though somewhat whitish, according to their chromatic sense is to them, owing to its intensity, a more evident representative of that colour than of violet" (*Optique Phys.*, p. 393).

In addition to this, one or two other facts are to be noted. If there are only two colours perceived, an equal admixture of them, which will be the sum of all possible colour sensations, should give a sensation of white, and,

theoretically, I cannot see why this white, since it is the sum of all the sensations which the eye is capable of receiving, should not be as intense as the white resulting from the admixture of the three fundamental colours perceived by the normal eye. When a solar spectrum is looked at, the point where the two colours pass over into each other is, according to this theory, gray or neutral (the line *N*). It should be found in what is the bluish-green to the normal eye close to the blue in the red-blind and close to the green in the green-blind.

So much for theory. How does it stand the test of experiment? Careful and conscientious examinations have been made by several competent individuals of a number of persons suffering from abnormal colour-perception, and we will now proceed to see how far they corroborate the theory as set forth by its most illustrious expounder.

It must be admitted at the outset that a great many difficulties surround a proper examination of abnormal colour-perception, difficulties which no one system of examination has been able to surmount. One of the chief obstacles in the way is the lack of any reliable faculty of comparison in the mind of the person examined. The individual sees clearly and distinctly but two colours in the spectrum, we will say. Now all the colours which the normal eye perceives must be referred by him to one or the other of these two. The only distinction between the colours falling under one or the other head is one of intensity (or it may be some other character which those with normal colour-perception take no note of); and as colours of the same character differ much in intensity and many shades of different colours have the same intensity, the confusions and mistakes likely to arise are almost without number.

Holmgren and many followers of the Young-Helmholtz theory consider that they are able to make a differential diagnosis of the three kinds of colour-blindness by the mistakes that are made in matching colours. There can be no question that this method is most admirably adapted for the detection of abnormal colour-perception, but certainly there is grave doubt as to its being infallible for differential diagnostic purposes.

Prof. Pflüger¹ made an examination of a number of colour-blind by various methods, with the sole object in view of testing their efficiency in this particular. The details of these examinations we have not the space to give, but the subjoined abstracts of the results throw, we think, a flood of light upon the question—or, put it in another form, intensify the darkness which surrounds it—if we are to accept the Young-Helmholtz theory:—

“In the above series of examinations the first six individuals have this in common, that for them there was no shortening in the bright spectrum, and that the maximum of brilliancy lay in the yellow (for Mr. St. in the orange). According to Donders and others, we should have diagnosed green-blindness. The last five have a shortening of the red end of the bright spectrum, and the maximum brightness is moved for them into the yellow-green. According to the same theory, these

¹ Archives of Ophthalmology, vol. ix. p. 435 *et seq.*

five cases must be set down as red-blind. If the shortening of the red end of the spectrum and a certain position of the maximum of brightness are to be used in dividing Daltonians into red-blind and green-blind, it is to be expected that yet other characteristics should be found which would differentiate the one kind of colour-blindness from the other. The above cases, however, show that certain essential qualities belong to representatives of both classes, and, on the other hand, great differences are to be found in the same class. . . . A common characteristic of all the eleven examined is that violet was designated as blue; further, a large number showed a shortening of the left end of the spectrum on diminution of intensity of the light, while to the normal eye there was no such shortening.

"It is interesting to note that a green-blind and a red-blind saw a neutral gray band in the blue-green which the others did not.

"In both classes there were found individuals to whom the spectrum was unqualifiedly dichromic.

"Mr. St. without, and Dr. Z. with a shortened red end of the spectrum distinguished the spectral red, yellow, green, and blue; they not only designated these colors by the right names, but matched them with saturated shades; and when an isolated band of these colours was brought before them there was no confusion in matching them and in the examination with Hirschberg's apparatus the same bands were superposed as identical."

. . . "From this series of examinations it again becomes evident how great are the individual differences in the cases of red-green blindness, and how fruitless the endeavour to unite the numerous varieties of the ordinary class of colour-blindness under two well-characterized subdivisions. The shortening of the red end of the spectrum and the relative brightness in the separate parts can scarcely explain the great difference in the appearance of the spectral colours to the different individuals. The curve of the brightness for the red- and green-blind cannot be typical, because: 1. The shortening of the red end of the spectrum is by no means the same in all the cases; and 2. because the maximum of brightness for each subdivision fluctuates considerably within a certain space.

"Completely green-blind people, Donders says, distinguish in a methodical examination five points in the solar spectrum. Points one and two are the limits of the two ends of the spectrum; three the neutral line *n* which appears gray; and four and five the localities which correspond respectively to yellow and blue. A gray neutral zone was observed in only two cases, once in a red-blind, according to the theory, and once in a green-blind."

Donders says further: "A comparison of the fixed with the movable spectrum shows that for the green-blind the colours on either side of the neutral band remain unaltered. On the other hand, the red-blind often begin, at the junction of the orange and red, in an equal illumination to distinguish a difference in colour, which is seen in the movable spectrum as red and in the stationary one as yellow. I have not been able, as seen from the detailed cases, to verify this law from my own observation."

In speaking of the examination by means of Radde's colour chart, he says:—

"The division into red- and green-blindness based on the shortening of the right end of the spectrum and the relative brightness of the various parts, does not find any corroboration in these observations. On the contrary, they show that the red- and green-blind make the same kind of mistakes, however great the personal variation may be. Here also, as in the examination with the spectral colours, we cannot successfully explain the differences in the condition of the colour-blind, simply by mistaking the intensity of light for colour."

In summing up his conclusions after examination by coloured shadows, he says:—

"This very great individual difference in the reaction of our ten colour-blind to the coloured shadows again proves the great variety in the kinds of colour-blindness and shows also that we are not able as yet to lay down any general laws in regard to the defect and that there is no genuine reason for the division

of the anomaly into red-blindness and green-blindness. Our results negative the theory that every red-green blind must see objective green and red as yellow, while green and blue must be classed with the subjective red called forth by contrast."

In speaking of the results of the examination by the Holmgren test he says :—

"The above observations show in a remarkable manner what has been asserted by many, and especially by Cohn that the results of Holmgren's method militate rather against a division of the colour-blind into red- and green-blind, and also against the theory of Young-Helmholtz, which Holmgren accepts as the basis of his theory. According to Holmgren, A. S., B. S., K., St., W., G. R., and O. R. Sr., are green-blind as well as red-blind. Z. was, according to Holmgren, green-blind, and yet since he had a shortening of the red end of the spectrum he must be red-blind."

In the examination of several colour-blind by more than one method, Magnus¹ found the spectrum dichromic (yellow and blue) both in red and green-blindness, though in red-blindness a few of the individuals said they distinguished more than the two colours; these statements, however, were not definite or satisfactory. Sometimes they would match red with brown wool, and would match a colour they called red with green, and a green with gray or brown.

In *green-blindness* the *lithium* (red) line of the spectrum was matched with various shades of red and yellow, beginning with the most saturated and going to the lightest brick-red approaching to the orange. The *thallium* (green) line was matched with brown, but often with white or gray from brightest to darkest, mixed sometimes with yellow or blue; also with the red from light flesh-colour to dark purplish. The *sodium* (yellow) was often called red, but always matched with yellow.

In *red-blindness* the *lithium* (red) line was nearly always matched with green, but of various shades from the lightest to the darkest, a few times with medium gray or brown. The *thallium* (green) line was matched frequently by green of the same shade as was used in matching the lithium, but often with other shades. The *sodium* (yellow) line was matched occasionally with green, but mostly with yellow.

Mauthner,² in the spectral examination of red-green blindness (according to Hering), found the spectrum dichromic, being composed of yellow and blue. The greatest intensity was, as in the normal eye, at the yellow, and there was no gray line between the colours; the line of demarcation was near Fraunhofer's *b*. There was no shortening of the violet end of the spectrum, but of the red end. Spectral red was distinguished, but only up to *B*. The spectrum was matched with only two colours—yellow and blue.

Cohn (*Studien u. angeb. Farbenblindheit*, 1879) made an examination of one hundred colour-blind by means of all the known methods, and from his general conclusions we select the following :—

¹ Archiv f. Oph., B. xxiv. 4.

² Vortrage a. d. Geb. d. Augenhulk, B. i. p. 207.

"15. Visual acuteness does not suffer in the colour-blind."

"21. Yellow and blue were never confounded by the red-green-blind with any other colour."

"47. The brightest portion of the spectrum lay for the most part, in the red-green-blind, in the yellow. In 12 only was it in the yellow-green."

"48. In only two persons was there a shortening of the spectrum, and that was at the red end."

"55. Every red-blind is also green-blind, and every green-blind is red-blind."

In comparing the results of these examinations, made by men of recognized ability and capacity for the work, and conducted solely with the view of arriving at the truth, with the phenomena which the Young-Helmholtz theory, as stated on page 72 *et seq.*, demands, it will be seen at once that they are far from harmonizing. An individual who is red-blind by one method of examination, is pronounced green-blind by another. There is shortening of the red end of the spectrum in the supposed green-blind. There is no gray or neutral line (*n*) in cases where it ought to be found, and when present, is often situated where it should not be. There seems to be but seldom any loss in brilliancy of the spectrum as a whole, and the brightest part is nearly always found in the yellow, as in the normal eye, and there is no sort of regularity in the manner in which the lost colours are matched. The only two colours about which mistakes are not made, are yellow and blue; all other colours are liable to confusion, and in the most unexpected and heterogeneous manner.

The failure of Hering's theory to account consistently for the phenomena of colour-blindness (so called) is equally obvious. In the ordinary form of abnormal colour-perception, there is an inability to properly distinguish shades of red and green. It cannot be denied that these colours are *seen*, and that they are distinguished as *colours*, though not in the same manner as in the normal eye, but *never* as simply black or white. Moreover, when the spectrum is looked at, with few exceptions, these colours are as intense as to the normal eye. How then can Hering's theory explain the phenomena? Red and green make an impression—and an impression as strong, so far as we are capable of judging, as these colours do in a properly colour-perceiving eye. It is impossible, therefore, to suppose, that a substance capable of being acted on by red and green waves is *lacking*. It can only be supposed, under these circumstances, that in the absence of the red-green substance, the yellow-blue substance acts vicariously, and in addition to its own colours, receives also those peculiar to the red-green substance—a fact which strikes at once at the foundation of the theory, and renders it totally inefficient, not to say absurd.

It will be seen, too, that both these theories make the cause of congenital abnormal perception of colours to be resident in the retina. This arises, in part at least, from the fact that they have made the retina a differentiating instead of a receptive and conducting apparatus. This, as we have already pointed out, has no analogy in any other function of the animal economy, except, perhaps, in the case of the ear. But here

the similarity was shown to be more apparent than real. If, as Helmholtz assumes, the organ of Corti has a cord which, by its length and tension, is tuned to every tone which the ear is capable of perceiving, this organ does indeed differentiate as well as transmit vibrations. But here the similarity between the eye and ear ceases, for in the ear the cords respond to vibrations to which they are attuned in accordance with the physical laws of sound, each cord being affected by vibrations of a certain length, and by no others. In the eye, however, each fibre or chemical substance is supposed to answer to all the primary colour vibrations, and to be more easily and readily affected by some than others, and by those, too, which do not bear any relation to each other that is required by the rules of harmony.

But little attention has been given in the discussions of colour-blindness to the part played by the brain in either normal or abnormal colour-perception. The fact that we see with the mind and not with the eye, seems to have been entirely ignored by the partisans in their zeal for one or the other theory. It has been sought to explain all the phenomena of colour-perception, normal as well as abnormal, by means of a normal or abnormal state of the retina, although all must know that no impression can be converted into a sensation except it reach the brain and be properly acted upon by the organ which presides over the function of vision.

Classification of Abnormal Colour-perception.—It is only fair to assume, and the facts in the case amply warrant the conclusion, that an abnormal state of any part of the nervous apparatus of vision—retina, optic nerve, or cerebral centre—would cause some alteration in the normal sensation. Thus we have changes in colour-perception when the retina is affected alone, and when the optic nerve is affected alone. There are likewise states in which we are forced to believe that the fault lies in the cerebral centre. The abnormal colour-perception observed in alcoholism can be much more satisfactorily accounted for by supposing the central organ of vision to be affected than on any other ground, and the phenomena of altered colour-perception manifest in the condition of hypnotism, are clearly cerebral in their character. I am yet at a loss to understand why it is that the brain should have been so persistently overlooked in the explanation of the manifestation of abnormal colour-perception. The name, colour *blindness*, which has been given to the condition, may have had something to do with it. This, of course, is a misnomer, for very few of those thus affected are in reality blind to any colour. The difficulty they labour under is a want of the power to properly distinguish certain shades from certain other shades. It would be absurd to say, because a man could not distinguish certain shades of red and green from each other, that he was blind to either—that he could not see them at all. He does see them, and sees them as colours just as he sees yellow and blue as colours, but he is not able to separate the impression made by the one from that made

by the other. All we know in regard to the differentiation of impressions points to the brain as the place where the final process leading to judgment takes place, and it cannot be denied, that except in rare cases, where there is a shortening of the spectrum, the mistakes of the colour-blind, so called, are errors of judgment.¹

To refer all kinds of abnormal colour-perception, therefore, to abnormal conditions of the retina would be clearly wrong. They might, however, be properly divided into two general classes, *central* and *peripheral*. In the former the difficulty would lie in the brain, and to it would belong all those cases of congenital origin in which the spectrum is not shortened, and even some of those in which it is. To the latter, the majority of cases acquired through inflammatory or other changes in the retina or optic nerve, and some of the cases probably in which the spectrum appears shortened. To this part of the subject, however, we will refer further on.

A New Theory of Colour-perception.—We think it must now be apparent that none of the theories of colour-perception which have been advanced hitherto can account in a consistent manner for all the phenomena of normal and abnormal coloured-vision, and that, moreover, there are certain objections on physical grounds which, with our present knowledge of the laws of molecular and wave-motion, are insurmountable. Can there, then, be no theory framed which will meet the requirements of the case in the light of recently acquired knowledge? We think there can. In the first place, it is essential to do away with the idea of the retina as a differentiating organ. This, however, will be easy, since there are no physical, anatomical, or physiological grounds for so considering it. The retina should be looked upon simply as a receiving and transmitting structure which shall give up faithfully to the optic nerve the impressions made upon it by the waves of the luminiferous ether. These impressions are carried by the nerve to the brain and are there properly differentiated and converted into sensations. Accepting this view, our task is very much simplified, and we believe that by this means all the phenomena of colour-perception and colour-blindness can be explained in a natural and consistent manner without the necessity of imagining new tissues or novel or unusual reactions of these tissues to light. *We consider the retina to be a substance whose ultimate structure is such as to allow it to respond at one and the same time to a large number of ethereal vibrations; at least such a number as shall be represented by the clearly distinguishable colours of the spectrum.*

This, it will be seen, is going back to the original theory of Newton, and simply adapting the undulatory theory of light to his hypothesis. Instead of the retina being affected by the “nature and bigness” of the

¹ Prof. Mauthner has suggested the terms *erythrochloropia*, or red-green vision, and *xanthokyanopia*, or blue-yellow vision, as substitutes for the names of red-green blindness and blue-yellow blindness. Theoretically, the idea is a good one.

"light corpuscles," we assume it to be affected by the varying number and size of the ethereal undulations. The arguments on theoretical physical grounds (or rather the assumption of such grounds), which had been advanced by Young, we have already attempted to meet in the earlier portion of this paper (page 72). Are there any facts which seem to point in a more positive manner to such ability as we have assigned to the retina? In other words, what is the character of the action of light upon the ultimate structure of substances?

We know that the action of light which we call chemical is exerted on the ultimate particles of a substance by causing an alteration in the relations between the molecules or atoms; and we likewise know, from the experiments of Prof. A. G. Bell, that the electric conductivity which is governed by the molecular structure of a substance is influenced by the action of light. It is on the varying action of light (as regards its *intensity*) on the molecular structure of selenium and other substances that the photophone is constructed. But Prof. Bell has found that this sensitiveness of selenium, for instance, to the action of ethereal waves is not confined to their force, but that the wave-length has also an influence. He has found in his experiments that different coloured lights produce different effects just as different intensities do. If this is true of the inorganic substances, is it not most reasonable to suppose that such an action should find its expression in the same or even a higher degree in a structure so highly organized as the retina? It is a perfectly legitimate supposition that the more delicately constructed the tissue the more sensitive it would be to such actions.

These views of the structure of the retina and the method of light action thereon were set forth in a preliminary paper on the subject of colour-blindness and colour-perception published in the *Archives of Ophthalmology* for March, 1881. They met with favourable notice from several European investigators, among whom was M. Giraud-Teulon, who incorporated them in a paper published in the *Annales d'Oculistique*, January to April, 1882, in answer to and in criticism of an article by Prof. Donders published in the same journal for November-December, 1880, entitled "Remarques sur les couleurs et la cécité des couleurs." In the number for May-June, 1882, of the same journal, Prof. Donders replies to the strictures of M. Giraud-Teulon, and discusses among other points the method of transmutation or transference of retinal impressions.

"Light may act in two ways, essentially different from each other; it may produce a *chemical* change, and furnish thereby only its equivalent energy; or it may put a molecule in motion, and in this manner give an impulse to a process from which will result an amount of chemical energy entirely *disproportionate to that of the light*."

As an example of the first kind of energy, he cites the action of light on the green substance of plants; as an example of the second kind, the result of a ray of light on a mixture of chlorine and hydrogen, producing

a force of explosion immeasurably beyond the original power of the light causing it. Donders thinks that the action of light on the retina is analogous to this last, and gives in support of this opinion, among others, the following quotation from M. De War on the currents of electricity produced by the action of light on the retina: "All experiments made up to this time have demonstrated that a quantity of light 100 times greater than another only increases the electric value 3 to 5 times beyond the original."

And in view of these facts Donders makes the following statement:—

"Certes, si le docteur Swan Burnett, cité avec une certaine complaisance par M. Giraud-Teulon, avait dûment distingué entre l'action primaire et secondaire de la lumière, il n'aurait pas proposé une théorie purement physique, qui cherche à illustrer ce qui se passe dans la rétine par le rôle du silénium dans le photophone." (p. 207.)

In reply to this stricture of the illustrious savant of Utrecht, it should be said, in the first place, that I have never contended that the action of light on the retina was "purely physical" in the ordinary acceptation of the term. However, it may be that we have not the same understanding of the word "physical." With our present knowledge of the action of the physical forces (heat, light, electricity, etc.) on the ultimate structure of substances, it is clearly impossible to draw the line sharply between "purely chemical" and "purely physical" actions, for even in the purely chemical the result is attained by a physical displacement or alteration in the relation of the atoms. Any difference between the two must, therefore, be one of convention. As, however, the changes which take place in the retina are not permanent, but follow each other in quick succession and pass off with comparative readiness, bearing an analogy in this respect to the vibrations of strings, membranes, etc., I think the term physical would be the more appropriate.

But after all, it matters not, as far as regards the theory, whether the action of light is "primary" or "secondary," so long as each impression is conveyed either in its original form or modified, separately and distinctly, to the brain. Each individual action (as caused by separate wave-lengths) may be diminished or increased in its energy or even changed as to its character, but it still remains distinct from the others, and this is all we contend for or require. Indeed, it does not seem at all improbable that the wave-motion of the ether does undergo a change in the retinal tissue, and that the effect of it is to influence the "nervous conductivity"—to use a very indefinite term—just as the ether waves affect the "electric conductivity" of the silénium in the photophone, but in either case the final result is different for each distinct impression, and in both cases the retina and silénium are receiving and conducting tissues. Therefore, as far as concerns our theory, it is a matter of no special consequence whether we "distinguish between the primary and secondary action of light."

Explanation of the Phenomena of Defects in Colour-perception by the New Theory.—In the first place, it is highly important that the term “colour-blindness” be entirely done away with, except where it can be appropriately applied to those rare cases in which there is absolutely no distinction of colour, all objects appearing as black or white or some shade of gray. For that large mass of cases in which there is only confusion of colours clearly distinguished by the ordinary eye, the term “abnormal colour-perception,” we think, would be more appropriate. The name is comprehensive, describes the condition with sufficient accuracy, and has no special theory lying back of it. The phenomena of abnormal colour-perception will require different explanations according as they fall under the heads of “central” or “peripheral,” as mentioned in a preceding section. The “central” forms, having their seat at the cerebral centre of vision, and being mere errors of judgment, must be explained on the general principles of sense-perception. In such cases we need not suppose the retina to be in an abnormal condition at all. The state of its molecular structure may be physically and physiologically perfect, and it may take up with the greatest faithfulness all the separate vibrations of the ether falling in it and transmit them, by means of the optic nerve, to the cerebral centre, and yet this centre may not be able to properly separate the different phases of vibrations received.

It must be remembered that the majority of those having defective colour-sense see the spectrum dichromic, the dividing line being about the beginning of the blue. We will assume in such cases (though the principle is applicable to all), that the cerebral centre is not able to differentiate clearly between the vibrations corresponding to those colours which lie on either side of the line, and which the normal eye can readily separate. I do not mean to say that in all cases the red, green, and yellow waves make precisely the same impression on the cerebral atoms. I believe they do not, but in the judgment of the individual they are, on account of his obtunded colour-sensibility, so nearly alike that he is *likely* to confound them, though as a matter of fact he does not always do so in all their shades. When there is a shortening of the spectrum it does not follow by any means that the fault lies in the retina. It may mean that the vibrations corresponding to the missing part of the spectrum fail to excite the cerebral molecules. There is a restricted range of visual sensation.

As before mentioned, we think this form of defective colour-perception could very properly be called *central*, and under it can be classed the large majority of the cases of abnormal colour-sense. It must not be forgotten that the sense of colour is after all the result of a process of education, by which the individual is enabled to separate varying impressions into distinct sensations, and in defective colour-perception we can and do have all grades of incapacity. Holmgren found it im-

possible to make any clear and distinct line of separation between what he called "colour-blindness" and a "diminished chromatic sense," that is, between those who confused the colours, which were clearly distinguishable by the ordinary eye, and those who could not distinguish between the finer shades of the same or allied colours. It is utterly impossible to account satisfactorily for such phenomena on any other basis than defective judgment. We therefore look upon so-called "colour-blindness" as but an exaggerated condition of "diminished chromatic sense."

The "peripheral" forms of defective colour-sense would depend upon an inability of the retina to take up certain vibrations, or of the optic nerve to carry them. It is a perfectly justifiable supposition that the retina responds to some ether-waves much more readily than to others, and that the optic nerve fibres carry certain wave motions more easily than others; that they seem to be unaffected by the ultra-red or ultra-violet rays is sufficient proof of this. Any alteration in the molecular structure of either (inflammation, partial atrophy, etc.) would, therefore, very likely affect their receptivity and conductibility, or there might be a congenital defect in the molecular structure of these bodies which would lead to the same result. The defects in colour-perception, therefore, attendant upon clearly marked changes in the optic nerve and retina, we would class distinctly under "peripheral," while some cases of congenital defect are probably of the same nature.

Support of the New Theory from Biology and Embryology.—In our explanation of colour-perception we have assumed that the sense of colour is but a very highly developed sense of temperature.¹ That is, that the optic nervous apparatus is but a very highly organized nerve of common sensation, and that both are affected by that form of radiant energy we know as ethereal vibration, and that the only difference between the two consists in the fact that in the process of evolution the nerves concerned in vision have become more and more adapted to the alterations produced in their molecular structure by the *quality* of the vibrations as expressed in their different wave-lengths. It now remains to show how far this opinion has its basis in the facts of biology and embryology.

On this subject we can quote no higher authority than that of the lamented F. M. Balfour, whose early death is little less than a calamity to science. In his *Comparative Embryology*, 1881, vol. ii. p. 387, he says :—

"In the lowest forms of animal life the whole surface is sensitive to light, and organs of vision have no doubt arisen in the first instance from limited areas becoming especially sensitive to light in conjunction with a deposit of pigment. Lens-like structures formed either as a thickening of the cuticle or as a mass of cells were subsequently formed; but their function was not in the first instance to throw an image of external objects on the perceptive part of the eye, but to concentrate the light upon it. From such a simple form of visual organ it is easy to pass by a series of steps to an eye capable of true vision."

¹ Preyer, *Archiv f. d. ges. Phys.* xxv. 1881, has gone into this question in great detail.

And again :—

“ It seems probable that the percipient elements of the retina are formed in all cases from the epidermis.”

All our knowledge of embryology tends to substantiate the supposition that the optic nerve is but a highly specialized nerve of common sensation, and the retina a modification of the integument in which the nerve terminates.

Mr. G. J. Romanes has made a number of elaborate and careful experiments upon the *medusæ*, an account of which will be found in the *Fortnightly Review*, 1878, p. 522 *et seq.* He found that the marginal surface of the bell is susceptible of stimulation, by light of any kind or variety, leading to a contraction of the body.

“ Probably,” he says, “ we have here the most rudimentary type of a visual organ that is possible ; for it is evident that if the ganglionic matter were a little more stable than it is, it would either altogether fail to be thrown down by the luminous vibrations or would occupy so long a time in the process that the visual sense would be of no use to its possessor.”

The time taken for the stimulus of light to be followed by contraction was about one second.

We quote the following passages from Mr. Herbert Spencer’s *Principles of Biology*, vol. ii.

“ That eyes are essentially dermal structures seems scarcely conceivable. Yet an examination of their rudimentary types and of their genesis in creatures that have them well developed, shows us that they really arise from successive modifications of the double layer composing the integument. They make their first appearance among the simpler animals as specks of pigment covered by portions of epidermis slightly convex and a little more transparent than that around it. Here their fundamental community of structure with the skin is easy to trace ; and the formation of them by differentiation of it presents no difficulty.” (p. 303.)
 . . . “ In a rudimentary eye we have but a slight peripheral expansion of a nerve to take cognizance of the impression ; and to concentrate the impression upon it there is nothing beyond a thickening of the epidermis into a lens shape. But the developed eye shows us a termination of the nerve greatly expanded and divided to receive the external stimulus. It shows us an introverted portion of the integument containing the apparatus by which the external stimulus is conveyed to the recipient nerve. The structure developed in this sac not only conveys the stimulus, but also, like its homologue, controls it ; and in the one case as in the other the structure which does this is an epidermic growth from the bottom of the sac.” (p. 306.)

“ Possibly, too, the light itself to which the tissues of some inferior animals are everywhere sensitive, may aid in setting up certain of the modifications by which the nervous parts of the visual organs are formed, producing, as it must, the most powerful effects at those points on the surfaces which the movements of the animal expose to the greatest and most frequent contrasts of light and shade ; and propagating from these points currents of molecular change through the organism.” (p. 307.)

To those who accept the evolution theory, these facts must seem conclusive. Even before the development of an eye proper there appear to be molecular changes wrought in the nerves of common sensation by the different wave-lengths which are sufficient to cause separate sensations.

In the further advance in evolution, therefore, it does not seem necessary to assume a total change in the character of the wave-action on the nervous substance, but only an increase in the delicacy of its action and its specialization in certain parts of the surface; those grosser ether waves which belong to the domain we call heat affecting all but an inconsiderable portion of the superficies, the finer which fall in the domain of light affecting that portion restricted to the organs concerned in vision.

The Part of the Retina concerned in Colour-perception.—It will not be inappropriate in a paper like this to offer some suggestions as to the part of the retina concerned in the reception of the vibrations which are afterwards perceived by the brain as colours. For a long time the layer of rods and cones has been accepted as a “percipient layer” of the retina. Professor J. W. Draper, of New York (*Physiology*, 1856), advanced the idea that it was the layer of hexagonal pigment cells which were acted on in a chemical manner by light, and that the sense of vision was the result of this chemical action, transferred to the brain by means of the optic nerve. That the vibrations do not affect the layer of rods and cones exclusively, as commonly accepted, seems proved by the fact, reported by Stricker (referred to in Hirschberg’s *Centralbl.*, July and August, 1883), that in a tiger, which during life had good visual power, there was found after death a complete absence of this layer. The same condition was likewise found in a leopard’s eyes. That the pigment layer is not essential is shown by the power of vision remaining in albinos, and in the lack of a scotoma in certain cases of coloboma of the choroid.

In the theory we have been considering, it is a matter of indifference what layer of the retina principally receives and takes up the ether vibrations, and then gives them over to the optic nerve fibres.

It is well known that the parts of the retina at the macula lutea are more sensitive than the more peripheral portions, and, carrying out Mr. Spencer’s idea, it may be with perfect fairness supposed that these must in time have become much more delicate in their responsive molecular movements than those peripheral parts which are less concerned in direct vision.

As bearing upon the part the retina plays in the reception of vibrations and the adaptability of its structure to different wave-lengths, it may be well to take note of what I call the “residual sensations” of white light, but which are commonly spoken of as “after-images.” More than ten years ago, when I first became skeptical as regards the adequacy of the Young-Helmholtz theory, I began to make experiments in this direction with the hope that the results might lead me into the way of finding a true theory of colours.

My object was to find through what phases of colour the after-image of white light would pass, from which I might be able to judge as to the relative power of the different waves to affect the retina. Simple as the

experiment may appear at first sight, its proper and satisfactory performance is not devoid of difficulty and complications.

The plan I finally fell upon was to place a bit of white paper on black ground in the clear sunlight, and expose my retina to it for a certain length of time and watch the changes of the after-image when the eye was closed and covered with the hands, so as to exclude all light. The character of the residual sensation varies within certain limits, with the time of exposure. I have not space to give all these experiments in detail, or even to give a general summary of the modification of the results by various circumstances. I must limit myself to the inference—which could hardly be called a law until it shall have been corroborated by other experimenters—I have been able to draw from those experiments which have been conducted under the most favourable circumstances and were freest from sources of error.

When the retina is exposed for from one to three or four seconds, according to the intensity of the light, the first coloured after-image is light violet or blue, which, if the light has not been intense, fades away either gradually to nothing or to a dirty yellow. If the exposure is longer, then other colours follow, and the order I have found, when the circumstances were most favourable, are light blue, deep rich blue or purple, reddish-purple, muddy yellow, reddish-orange, dark green, light red, dark red, black. I do not mean to say that in all of my experiments, which amounted to hundreds, this exact number of after-images occurred, but they always followed this order when they were observed. Thus red of any tint was never first observed, nor did green come before yellow or orange when they were both observed in the same experiment; moreover, except the blue and purple, few of the colours could be called pure (except occasionally the red), though exceptionally some of the others under certain circumstances would come out with startling distinctness.

The phases of colour of the after-images of white light, as given by Helmholtz (*Optique Physiologique*, p. 489), are greenish-blue, indigo, violet or rose, greenish-orange. When the light has acted for a longer time he then had white, blue, green, red, and blue on a black ground; on a white ground, white, green, and blue.

At the time I made my own first experiments I was not in a position to know those given by Aubert in his *Physiologie der Netzhaut* (1865), p. 372, and referred to in his *Physiologische Optik* (Gräfe u. Saemische, Handb. d. gesamt. Augenheilk, B. II. S. 559). After a momentary glance at the sun (which of course gives us the purest white light to be had), he found the order of the after-images to be light blue, light green, red. It appears that Fechner had observed the same order in his investigations (Poggend, Ann. 1840).

In the *Nineteenth Century* for October, 1883, Mr. Sidney Hodges gives the results of his experiments on these after-images, studying them in a

somewhat different way. He found, for instance, that the after-image of white light after ten seconds' exposure was blue, after fifteen seconds green, after twenty-five seconds yellowish-green or pure yellow. In the disappearance of these after-images (whether blue, green, or yellow), they always followed the same order: First, a dull orange, pink, deep pink, crimson, violet, blue. The length of time from the first perception of the after-image to its commencement to disappear varied with the length of the exposure. It is apparent, however, that Mr. Hodges has not been accustomed to making such experiments, and his results, for this reason, lose very much of their value.

There are certain discrepancies in this series of experiments by different observers which I cannot at present account for, but any one who has investigated at all in this field will at once appreciate the difficulty of obtaining uniform results under all circumstances, even after we shall have excluded the "personal equation." It must be remembered that we can never be sure when we have the retina in a state of perfect quietude. The movements of the lids, and of the balls, and even the intra-ocular circulation set up vibration in the retina, which always tends to complicate the result of the action of the white light. Rapid walking or other exercise will bring about such vibration, and a slight pressure of the lids or even the rotation of the globe, while studying the after-image, will always change its character. And it must also be remembered that unless we use direct sunlight or the electric light we can never be sure that we have the proper proportion of the various colours constituting white light. In almost if not quite all reflected light there is predominance of some one colour, which, however, would only reveal itself when viewed in contrast with pure white. How far these circumstances have tended to the different results in each case we have, of course, no means of determining. The only fact of importance which we can draw from them so far as the retina is concerned is its impressibility to the various colour-waves. From my own experiments I am led to infer that the shorter waves (blue) affect the retina most easily and strongly at first, and overpower the other vibrations by their intensity. They, however, are sooner exhausted than the others, which take a longer time to affect it, but whose vibrations last longer, just as we find it in the case of short and long strings, for example. It will be seen that the order of disappearance in my experiments follows pretty regularly the colours of the spectrum from the blue to the red end, and I am inclined to think that under entirely favourable circumstances this is the natural order, and in so far as that is true the residual sensation of white light would tend to support the new rather than the Young-Helmholtz theory, as being in keeping with the known laws of molecular vibration. It would, however, be much more in keeping with the Young-Helmholtz than the Hering theory. It strikes, to my mind, at the foundations of the latter, inasmuch as it makes white light act in the

greater and more lasting degree on the red-green and blue-yellow substance than on its own peculiar substance. But, after all, we must not be too hasty in concluding that the phenomena are wholly retinal. We have to do in these experiments, it must be remembered, with sensations, and the seat of sensation is in the cerebral centre. However, in any case we know that we are dealing with the result of wave and molecular motion, which, whether in the retina or the brain centre, must be in keeping by well-demonstrated physical laws.

Central Colour-perception.—After this endeavour to transfer the function of perceiving colour impressions from the retina to the brain, it remains to say something in regard to a possible manner in which these impressions are finally converted into colour sensations.

It must be confessed at the outset, that since we have abandoned, in a large measure, the domain of physics and physiology and have entered that of psychics, we shall be lacking in a most regretful degree in those positive data which have lain at the basis of our studies heretofore, and for demonstrable facts we must now substitute plausible speculation. It is not possible for the human mind to conceive how any impression is converted into a sensation. In our imagination we can follow the changes produced by the affecting agent, it may be up to the most delicate alteration in the ultimate atoms or molecules of the brain-substance, but between these atomic or molecular changes and the consciousness we demonstrate sensation there is a gulf fixed which is impassable by the finite mind. But up to the physical edge of the gulf we can legitimately follow the various stages of the phenomena.

The first question that would naturally arise is, whether there is a certain portion of the brain-substance set apart to preside over the function of the colour-sense. It seems now to be pretty conclusively demonstrated that there is a certain portion of the brain, situated in the cortical substance of the occipital lobe of the cerebrum, which is intimately connected with the function of vision. But, as the sense of vision comprehends the separate sensation of form—white- and coloured-vision, it is a pertinent question whether the same cerebral cells or molecules are concerned in the production of all three sensations, or whether there are separate centres for each.

If we allow that there are three separate centres, we must also admit three separate fibres going from each percipient element of the retina to each of the centres, since each separate percipient retinal element is concerned in all three functions. This would burden us with a multiplicity of fibres and lead us into a maze of complications from which it would be difficult to free ourselves. We should be likely on this theory to have an affection of any one of the centres, leaving the others intact, that is, we should have a distinct light-, form-, and colour-blindness.

No cases of separate light- or form-blindness have, so far as my knowl-

edge extends, been reported, but there are cases of hemi-achromatopsia (light and form sense being intact) on record, and these give sufficient plausibility to the supposition of a distinct colour-centre to warrant a consideration of its merits.

When we come to look at the phenomena of vision as a whole, we can divide them broadly into two classes: those of quantitative and those of qualitative distinction. The sense of form, so far as it relates to the sense of vision, we would suppose to depend upon the number of retinal elements affected, and their relations to each other in space. Colour we would look upon as the result of a discrimination between the changes produced by ether waves of different lengths; while the sense of light (white) would be the sum of all these wave impressions occurring at the same time. I would, therefore, suppose one cerebral atom or molecule corresponding to each percipient retinal element with which it is connected by means of an optic nerve fibre. In other words, the cerebral mass concerned in the reception and perception of the impressions made on the retina need not be greater than that of the retina itself, for if the mass of the retina is sufficient for their reception, a corresponding cerebral mass should be sufficient for their perception; and this, we think, taking into consideration the extent of gray matter in the convolutions is not making an excessive demand.

Are there then different parts of this mass set apart for the perception of the different colours? I do not see the necessity for this. I would suppose the cerebral molecules or atoms to be capable of vibrating in the same phases as their corresponding molecules in the retina, or, going farther back still, in the substance of the luminous body itself. Of course, under this hypothesis it is not demanded that there be a special phase of vibration for every distinctly-perceptible colour and shade. It is still possible to divide colours into "primary" and "combination." As for myself, I should regard as "primary" all those colours which are clearly distinguished as such in the full solar spectrum. All others I would regard as "combination colours."

Those cases of hemi-achromatopsia which have been observed, I would explain on the supposition that, from some cause, the cerebral molecules of one side were rendered incapable of responding to the phases which corresponded to the missing colour or colours, or it might be that pressure or other alteration in one optic tract prevented the fibres from carrying the wave-motion representing that colour from the retina to the brain.

Charpentier has endeavoured to prove that the perception of white light is distinct from that of colours. It is true that white light is perceived further towards the periphery of the retina than any single colour, and that some colours are lost before others—green, for instance, being the first to disappear, and blue last. But his own experiments have proved

when the *intensity* of green is increased sufficiently it can be distinguished as peripherally as blue. In other words, as we go towards the periphery of the retina we require a greater intensity of wave-action in order to have an impression. Now it must be evident that white light, since it is the sum of all colour-vibrations, must be more intense in its action than any one colour-vibration, and hence must be perceived more peripherally than any single colour. It seems, therefore, useless to suppose a separate centre for the perception of white light, and it is rendered doubly unnecessary from the fact that there is no white light which cannot be resolved into the spectral colours. It is a well-demonstrated fact in physics that white light is not simple but compound, and made up of different colours, and thus a centre for white must of necessity comprise a centre for all the colours of which it is composed.

As directly connected with the question of cerebral colour-perception we would call attention to the phenomenon of "coloured audition," instances of which have recently been brought to notice. In these cases certain notes (corresponding to certain definite aerial vibrations) have associated with their perception the sensation of certain colours. This is most satisfactorily accounted for on the supposition that the vibrations in the cerebral centre of audition, caused by the action of sound-waves on the terminal filaments of the acoustic nerve, have, in some manner, probably from close contact of the two centres, been communicated to the visual centre, since, according to the theory of the "specific energy of nerves," any disturbance of the molecules of the visual centre is associated with a sensation of vision. All this is in perfect keeping with the evolutionary development of the senses as now commonly held by biologists.



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